MECHANICAL BEHAVIOR OF MATERIALS

Engineering Methods for Deformation, Fracture, and Fatigue

Second Edition

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1.2.1 Elastic and Plastic Deformation

Deformations are quantified in terms of normal and shear strain in elementary mechanics of materials. The cumulative effect of the strains in a component is a deformation, such as a bend, twist, or stretch. Deformations are sometimes essential for function, as in a spring. Excessive deformation, especially if permanent, is often harmful.

Deformation that appears quickly upon loading can be classed as either elastic deformation or plastic deformation, as illustrated in Fig. 1.2. *Elastic deformation* is recovered immediately upon unloading. Where this is the only deformation present, stress and strain are usually proportional. For axial loading, the constant of proportionality is the *modulus of elasticity*, *E*, as defined in Fig. 1.2(b). An example of failure by elastic deformation is a tall building that sways in the wind and causes discomfort to the occupants, although there may be only remote chance of collapse. Elastic deformations are analyzed by the methods of elementary mechanics of materials and extensions of this general approach, as in books on theory of elasticity and structural analysis.

Plastic deformation is not recovered upon unloading and is therefore permanent. The difference between elastic and plastic deformation is illustrated in Fig. 1.2(c). Once plastic deformation begins, only a small increase in stress usually causes a relatively large additional deformation. This process of relatively easy further deformation is called *yielding*, and the value of stress where this behavior begins to be important for a given material is called the *yield strength*, σ_o.

Materials capable of sustaining large amounts of plastic deformation are said to behave in a *ductile* manner, and those that fracture without very much plastic deformation behave in a *brittle* manner. Ductile behavior occurs for many metals, such as low-strength steels, copper, and lead, and for some plastics, such as polyethylene. Brittle behavior occurs for glass, stone, acrylic plastic, and some metals, such as the high-strength steel

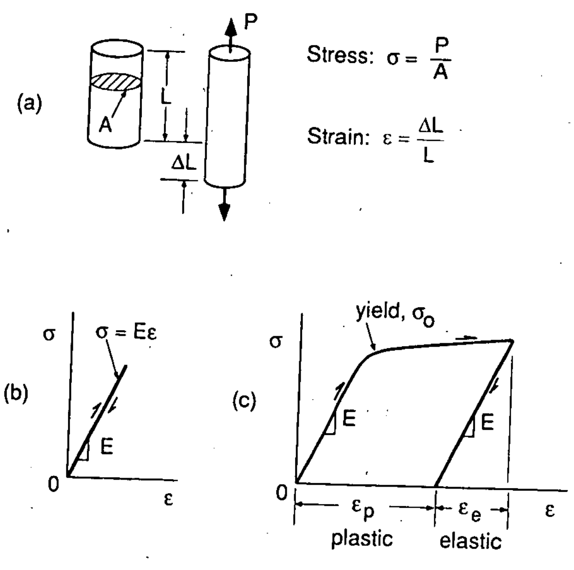

Figure 1.2 Axial member (a), subject to loading and unloading showing elastic deformation (b), and both elastic and plastic deformation (c).

used to make a file. (Note that the word *plastic* is used both as the common name for polymeric materials and in identifying plastic deformation, which can occur in any type of material.)

Tension tests are often employed to assess the strength and ductility of materials as illustrated in Fig. 1.3. Such a test is done by slowly stretching a bar of the material in tension until it breaks (fractures). The *ultimate tensile strength*, σ_u, which is the highest stress reached before fracture, is obtained along with the yield strength and the strain at fracture, ε_f. The latter is a measure of ductility and is usually expressed as a percentage, then being called the *percent elongation*. Materials having high values of both σ_u and ε_f are said to be *tough*, and tough materials are generally desirable for use in design.

Large plastic deformations virtually always constitute failure. For example, collapse of a steel bridge or building during an earthquake could occur due to plastic deformation. However, plastic deformation can be relatively small but still cause malfunction of a component. For example, in a rotating shaft, a slight permanent bend results in unbalanced rotation, which in turn may cause vibration and perhaps early failure of the bearings supporting the shaft.

Buckling is deformation due to compressive stress that causes large changes in alignment of columns or plates, perhaps to the extent of folding or collapse. Either elastic or plastic deformation, or a combination of both, can dominate the behavior. Buckling is generally considered in books on elementary mechanics of materials and structural analysis.

1.2.2 Creep Deformation

Creep is deformation that accumulates with time. Depending on the magnitude of the applied stress and its duration, the deformation may become so large that a component can no longer perform its function. Plastics and low-melting-temperature metals may

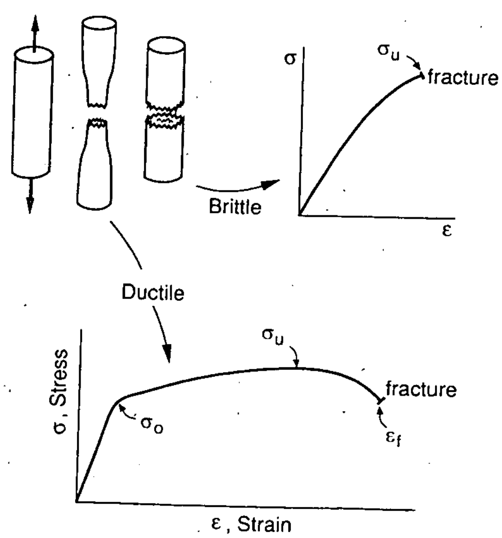

Figure 1.3 Tension test showing brittle and ductile behavior. There is little plastic deformation for brittle behavior, but a considerable amount for ductile behavior.

Test standards give the procedures to be followed in detail, but the theoretical basis of the test and background discussion are not generally given. Hence, one purpose of this book is to provide the basic understanding needed to apply materials test standards and to make intelligent use of the results.

Measured values of any property of a given material, such as its elastic modulus, yield strength, or hardness, are subject to statistical variation. This issue is often addressed in test standards, and it is discussed in Appendix B of this book. Note that multiple measurements of a given property are needed to obtain an average value and to characterize the statistical scatter about this average.

4.2 INTRODUCTION TO TENSION TEST

A tension test consists of slowly pulling a sample of material in tension until it breaks. The test specimen used may have either a circular or a rectangular cross section, and its ends are usually enlarged to provide extra area for gripping and to avoid having the sample break where it is being gripped. Specimens both before and after testing are shown for several metals and polymers in Figs. 4.5 and 4.6.

Methods of gripping the ends vary with specimen geometry. A typical arrangement for threaded-end specimens is shown in Fig. 4.7. Note that spherical bearings are used at each end to provide a pure tensile load with no undesirable bending. The usual manner of conducting the test is to deform the specimen at a constant speed. For example, in the universal testing machines of Fig. 4.3, the motion between the fixed and moving crossheads can be controlled at a constant speed. Hence, distance h in Fig. 4.7 is varied so that

$$\frac{dh}{dt} = \dot{h} = \text{constant}$$

The load that must be applied to enforce this displacement rate varies as the test proceeds. This load P may be divided by the cross-sectional area A_i to obtain the stress in the specimen at any time during the test.

$$\sigma = \frac{P}{A_i} \tag{4.1}$$

Displacements on the specimen are measured within a straight central portion of constant cross section over a *gage length* L_i as indicated in Fig. 4.7. Strain ε may be computed from the change of this length, ΔL.

$$\varepsilon = \frac{\Delta L}{L_i} \tag{4.2}$$

It is sometimes reasonable to assume that all of the grip parts and the specimen ends are nearly rigid. In this case, virtually all of the change in crosshead motion is due to deformation within the straight section of the test specimen, so that ΔL is approximately the same as Δh, the change in h. Strain may therefore be estimated as $\varepsilon = \Delta h/L_i$.

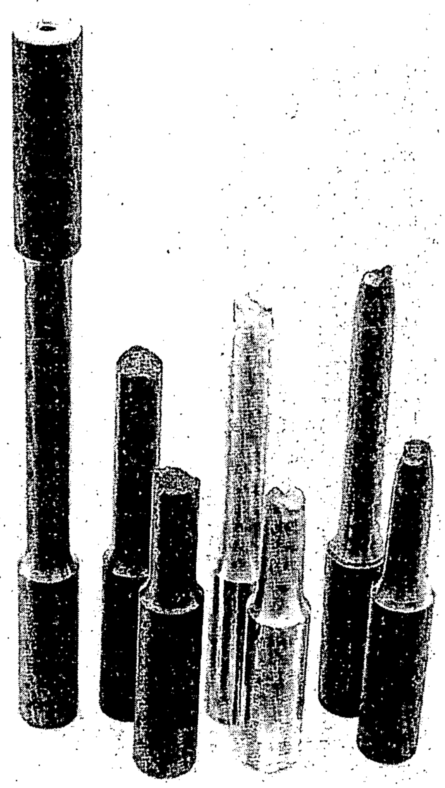

Figure 4.5 Tensile specimens of metals (left to right): untested specimen with 9 mm diameter test section, and broken specimens of gray cast iron, aluminum alloy 7075-T651, and hot-rolled AISI 1020 steel. (Photo by R. A. Simonds.)

However, actual measurement of ΔL is preferable. Stress and strain as above, based on the initial (undeformed) dimensions, A_i and L_i, are called *engineering stress and strain.*

The curve giving the relationship between engineering stress and strain during a tension test varies widely for different materials. *Brittle* behavior in a tension test is failure without extensive deformation. Gray cast iron, glass, and some polymers, such as PMMA (acrylic), are examples of materials with such behavior. A stress-strain curve for gray iron is shown in Fig. 4.8. Other materials exhibit *ductile behavior*, failing in tension only after extensive deformation. Stress-strain curves for ductile behavior in engineering metals and some polymers are similar to Figs. 4.9 and 4.10, respectively.

4.3 ENGINEERING STRESS-STRAIN PROPERTIES

Various quantities obtained from the results of tension tests are defined as materials properties. Those based on engineering stress and strain will now be described. In a later portion of this chapter, additional properties based on different definitions of stress and strain, called true stress and strain, will be considered.

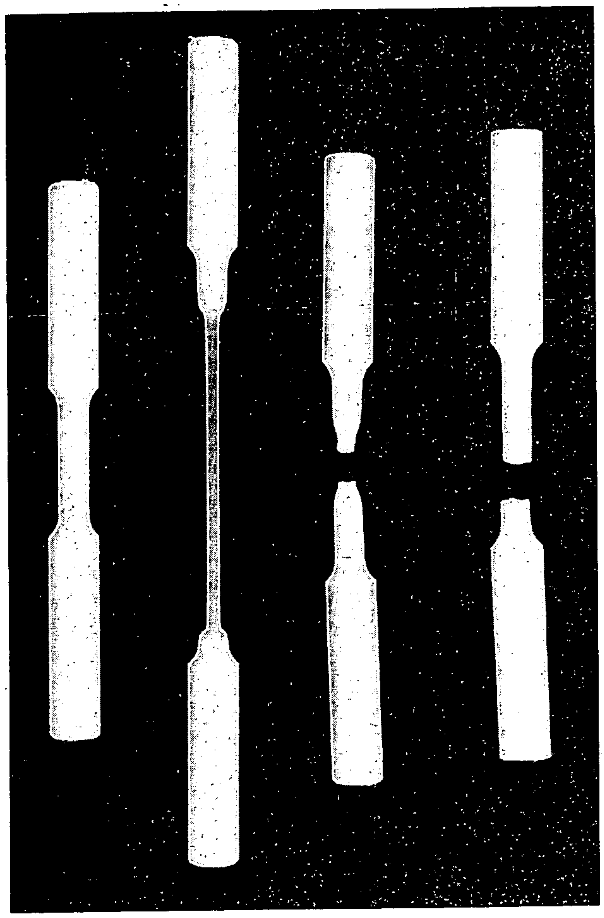

Figure 4.6 Tensile specimens of polymers (left to right): untested specimen with a 7.6 mm diameter test section, a partially tested specimen of high-density polyethylene (HDPE), and broken specimens of nylon 101 and Teflon (PTFE). (Photo by R. A. Simonds.)

4.3.1 Elastic Constants

Initial portions of stress-strain curves from tension tests exhibit a variety of different behaviors for different materials as shown in Fig. 4.11. There may be a well-defined initial straight line, as for many engineering metals, where the deformation is predominantly elastic. The *elastic modulus*, E, also called *Young's modulus*, may then be obtained from the stresses and strains at two points on this line, such as A and B in (a).

$$E = \frac{\sigma_B - \sigma_A}{\varepsilon_B - \varepsilon_A} \tag{4.3}$$

In other cases, there is no well-defined linear region. Here, a *tangent modulus*, E_t, may be employed, which is the slope of a straight line that is tangent to the stress-strain curve at the origin as shown in (c). As a practical matter, obtaining E_t often involves the use of considerable judgment, so that this is not a very well-defined property.

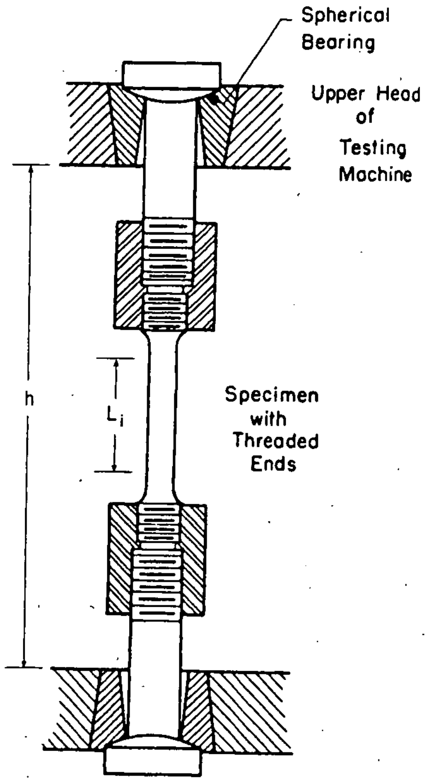

Figure 4.7 Typical grips for a tension test in a universal testing machine. (Adapted from [ASTM 97] Std. E8; copyright ©ASTM; reprinted with permission.)

Poisson's ratio ν can also be obtained from a tension test by measuring transverse strains during elastic behavior. Diameter measurements or a strain gage can be used for this purpose. (See the next chapter, Section 5.3, for detailed discussion of Poisson's ratio.)

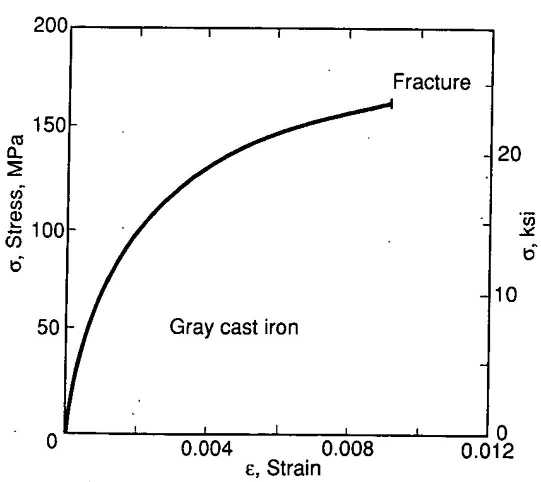

Figure 4.8 Stress-strain curve for gray cast iron in tension showing brittle behavior.

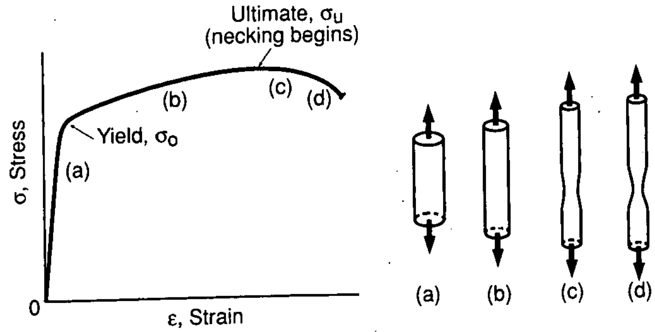

Figure 4.9 Schematic of the engineering stress-strain curve of a typical ductile metal that exhibits necking behavior.

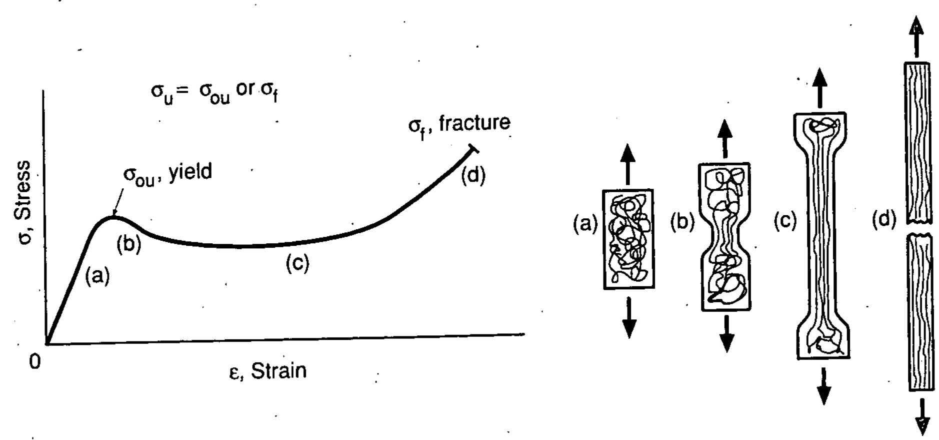

Figure 4.10 Engineering stress-strain curve and geometry of deformation typical of some polymers.

4.3.2 Engineering Measures of Strength

The *ultimate tensile strength*, σ_u, also called simply the *tensile strength*, is the highest engineering stress reached prior to fracture. If the behavior is brittle, as for gray cast iron in Fig. 4.8, the highest stress occurs at the point of fracture. However, in ductile metals, the load, and hence the engineering stress, reaches a maximum and then decreases prior to fracture, as in Fig. 4.9. In either case, the highest load reached at any point during the test, P_{max}, is used to obtain the ultimate tensile strength by dividing by the original cross-sectional area.

$$\sigma_u = \frac{P_{max}}{A_i} \tag{4.4}$$

The *engineering fracture strength*, σ_f, is obtained from the load at fracture, P_f, even if this is not the highest load reached.

$$\sigma_f = \frac{P_f}{A_i} \tag{4.5}$$

Hence, for brittle materials, $\sigma_u = \sigma_f$, whereas for ductile materials, σ_u may exceed σ_f.

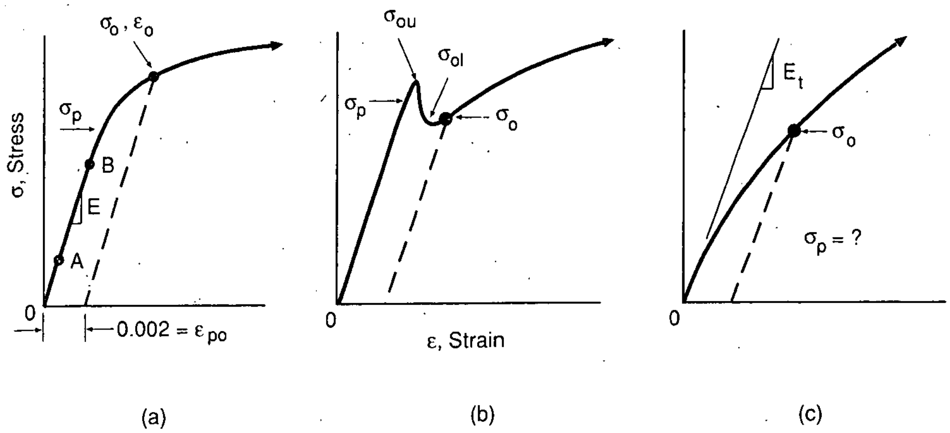

Figure 4.11 Initial portions of stress-strain curves: (a) many metals and alloys, (b) material with yield drop, and (c) material with no linear region.

The departure from linear-elastic behavior as in Fig. 4.11 is called *yielding* and is of considerable interest. This is simply because stresses that cause yielding result in rapidly increasing deformation due to the contribution of plastic strain. As discussed in Section 1.2 and illustrated by Fig. 1.2, any strain in excess of the elastic strain σ/E is plastic strain and is not recovered on unloading. Hence, plastic strains result in permanent deformation. Such deformation in an engineering member changes its dimensions and/or shape, which is almost always undesirable. Thus, the first step in engineering design is usually to assure that stresses are sufficiently small that yielding does not occur, except perhaps in very small regions of a component.

The yielding event can be characterized by several methods. The simplest is to identify the stress where the first departure from linearity occurs. This is called the *proportional limit*, σ_p, and is illustrated in Fig. 4.11. Some materials, as in (c), may exhibit a stress-strain curve with a gradually decreasing slope and no proportional limit. Even where there is a definite linear region, it is difficult to precisely locate where this ends. Hence, the value of the proportional limit depends on judgment, so that this is a poorly defined quantity. Another quantity sometimes defined is the *elastic limit*, which is the highest stress that does not cause permanent (i.e. plastic) deformation. Determination of this quantity is difficult, as periodic unloading to check for permanent deformation is necessary.

A third approach is the *offset method*, which is illustrated by dashed lines in Fig. 4.11. A straight line is drawn parallel to the elastic slope, E or E_t, but offset by an arbitrary amount. The intersection of this line with the engineering stress-strain curve is a well-defined point that is not affected by judgment, except in cases where E_t is difficult to establish. This is called the *offset yield strength*, σ_o. The most widely used and standardized offset for engineering metals is a strain of 0.002, that is 0.2%, although other values are also used. Note that the offset strain is a plastic strain, such

as $\varepsilon_{po} = 0.002$, as unloading from σ_o would follow a dashed line in Fig. 4.11, and this ε_{po} would be the unrecovered strain.

In some engineering metals, notably in low-carbon steels, there is very little nonlinearity prior to a dramatic drop in load as illustrated in Fig. 4.11(b). In such cases, one can identify an *upper yield point*, σ_{ou}, and a *lower yield point*, σ_{ol}. The former is the highest stress reached prior to the decrease, and the latter is the lowest stress prior to a subsequent increase. Values of the upper yield point in metals are sensitive to testing rate and to inadvertent small amounts of bending, so that reported values for a given material vary considerably. The lower yield point is generally similar to the 0.2% offset yield strength, with the latter having the advantage of being applicable to other types of stress-strain curve as well. The offset yield strength is generally the most satisfactory means of defining the yielding event for engineering metals.

For polymers, offset yield strengths are also used. However, it is more common for polymers to define a yield point only if there is an early relative maximum (upper yield point) or flat region in the curve, in which case σ_o is the stress where $d\sigma/d\varepsilon = 0$ first occurs. In polymers with an upper yield point, σ_{ou}, this stress may exceed that at fracture, σ_f, but in other cases, it does not. (See Fig. 4.10.) Hence, the ultimate tensile strength σ_u is the higher of either σ_{ou} or σ_f. The two situations are distinguished by describing the value as either the *tensile strength at yield* or the *tensile strength at break.*

In most materials, the proportional limit, elastic limit, and offset yield strength can be considered to be alternative measures of the beginning of permanent deformation. However, for a nonlinear elastic material such as rubber, the first two of these measure distinctly different events, and the offset yield strength loses its significance. (See Fig. 3.17.)

4.3.3 Engineering Measures of Ductility

Ductility is the ability of a material to accommodate inelastic deformation without breaking. In the case of tension loading, this means the ability to stretch by plastic strain, but with creep strain also sometimes contributing.

The *engineering fracture strain* is one measure of ductility. This is obtained from the length at fracture, L_f, of the gage section that originally had length L_i.

$$\varepsilon_f = \frac{L_f - L_i}{L_i} \tag{4.6}$$

Note that ε_f corresponds to the same point on the stress-strain curve as the engineering fracture strength σ_f. Often, ε_f is expressed as a percentage and is called the *percent elongation.*

$$\%\ \text{elongation} = 100\varepsilon_f \tag{4.7}$$

where ε_f is dimensionless according to Eq. 4.6.

For polymers, the ASTM Standards specify that the elongation is the value *at* fracture, as obtained from the stress-strain curve by taking the strain ε_f at the instant of fracture. However, for metals, the usual practice, and also the procedure in the ASTM

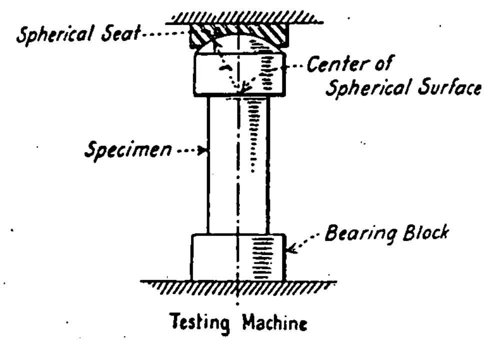

Figure 4.22 Compression test in a universal testing machine using a spherical-seated bearing block. (From [ASTM 97] Std. E9; copyright ©ASTM; reprinted with permission.)

alignment with respect to the testing machine. For example, the ends of the specimen can be almost parallel, but never perfectly so.

Conversely, if L/d is small, the test result is affected by the details of the conditions at the end. In particular, as the specimen is compressed, the diameter increases due to the Poisson effect, but friction retards this motion at the ends, resulting in deformation into a barrel shape. Although this effect can be minimized by proper lubrication of the ends, it is difficult to avoid entirely. As a result, in materials that are capable of large amounts of deformation in compression, the choice of too small of an L/d ratio may result in a situation where the behavior of the specimen is dominated by the end effects. Again, the test does not measure the fundamental compressive behavior of the material.

Considering both the desirability of small L/d to avoid buckling and large L/d to avoid end effects, a reasonable compromise is $L/d = 3$ for ductile materials. Values of $L/d = 1.5$ or 2 are suitable for brittle materials, where the small amount of deformation that occurs causes less difficulty with end effects.

Some examples of compression specimens of various materials both before and after testing are shown in Figs. 4.23 and 4.24. Mild steel shows typical ductile behavior, specifically large deformation without fracture ever occurring. The gray cast iron and concrete behaved in a brittle manner, and the aluminum alloy deformed considerably but then also fractured. Fracture in compression usually occurs on an inclined plane or on a conical surface.

4.6.2 Materials Properties in Compression

The initial portions of compressive stress-strain curves have the same general nature as those in tension. Thus, various materials properties may be defined from the initial portion in the same manner as for tension, such as the elastic modulus E, the proportional limit σ_p, and the yield strength σ_o.

The ultimate strength behavior in compression differs in a qualitative way from that in tension. Note that the decrease in load prior to final fracture in tension is associated with the phenomenon of necking. This of course does not occur in compression. In fact, an opposite effect occurs, in that the increasing cross-sectional area causes the stress-strain curve to rise rapidly rather than showing a maximum.

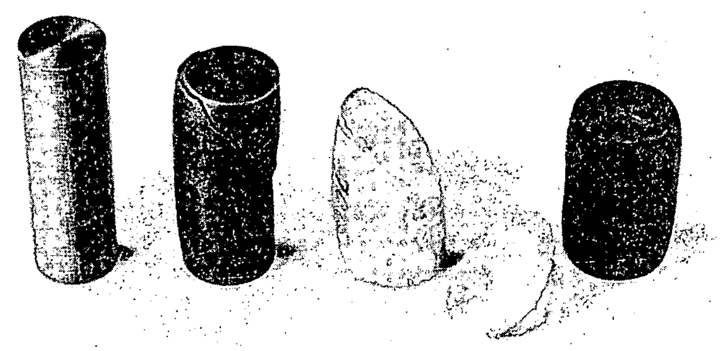

Figure 4.23 Compression specimens of metals (left to right): untested specimen, and tested specimens of gray cast iron, aluminum alloy 7075-T651, and hot-rolled AISI 1020 steel. Diameters before testing were approximately 25 mm, and lengths were 76 mm. (Photo by R. A. Simonds.)

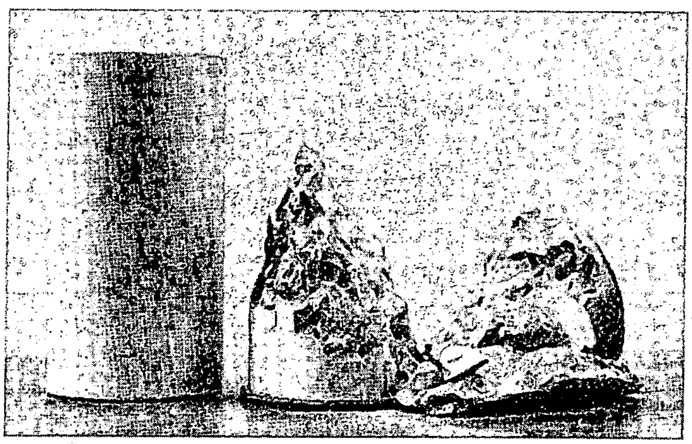

Figure 4.24 Untested and tested 150 mm diameter compression specimens of concrete with Hokie limestone aggregate. (Photo by R. A. Simonds.)

As a result, there is no load maximum in compression prior to fracture, and the engineering ultimate strength is the same as the engineering fracture strength. Brittle and moderately ductile materials will fracture in compression. But many ductile metals and polymers simply never fracture. Instead, the specimen deforms into an increasingly larger and thinner pancake shape until the load required for further deformation becomes so large that the test must be suspended.

Ductility measurements for compression are analogous to those for tension. Such measures include percentage changes in length and area, and also engineering and true

fracture strain. The same measures of energy capacity may also be employed, as can constants for true stress-strain curves of the form of Eq. 4.28.

4.6.3 Trends in Compressive Behavior

Ductile engineering metals often have nearly identical initial portions of stress-strain curves in tension and compression, with an example of this being shown in Fig. 4.25. After large amounts of deformation, the curves may still agree if true stresses and strains are plotted.

Many materials that are brittle in tension have this behavior because they contain cracks or pores that grow and combine to cause failures along planes of maximum tension, that is, perpendicular to the specimen axis. Examples are the graphite flakes in gray cast iron, cracks at the aggregate boundaries in concrete, and porosity in sintered ceramics. Such flaws have much less effect in compression, so that materials that behave in a brittle manner in tension usually have considerably higher compressive strengths. For example, compare the strengths in tension and compression given for various ceramics in Table 3.10. Quite ductile behavior can even occur for materials that are brittle in tension, as for the polymer in Fig. 4.26.

Where compressive failure does occur, it is generally associated with a shear stress, so that the fracture is inclined relative to the specimen axis. This type of fracture is evident for gray cast iron, an aluminum alloy, and concrete in Figs. 4.23 and 4.24. Compare the cast iron fracture plane with that for tension in Fig. 4.13. The tension fracture plane is oriented normal to the applied tension stress, which is typical of brittle behavior in all materials.

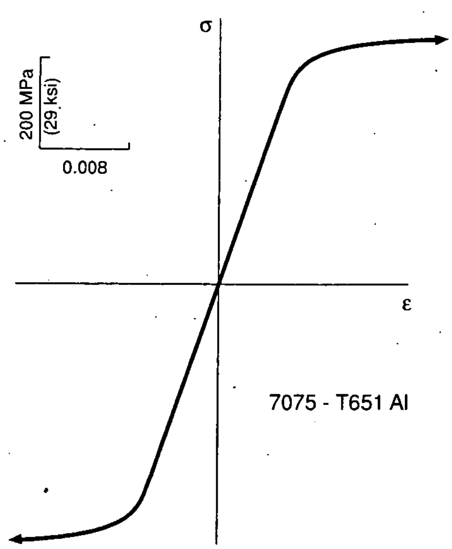

Figure 4.25 Initial portions of stress-strain curves in tension and compression for 7075-T651 aluminum.

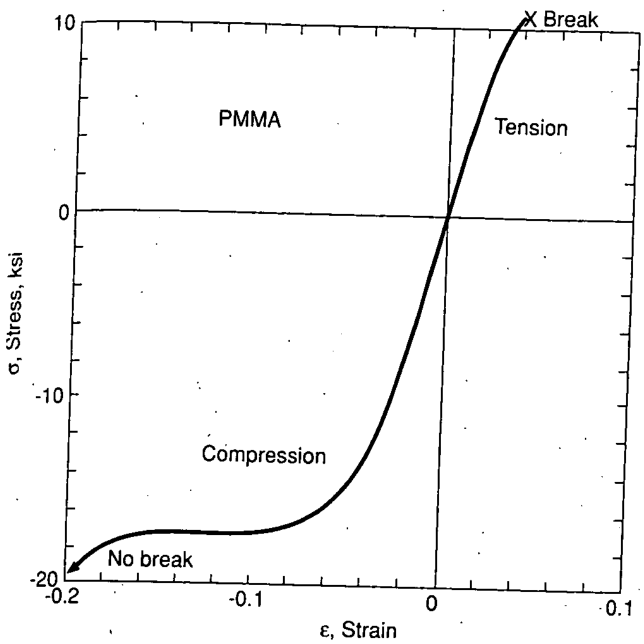

Figure 4.26 Stress-strain curves for plexiglass (acrylic, PMMA) in both tension and compression. (Adapted from [Richards 61] p. 153; reprinted by permission of PWS-Kent Publishing Co., Boston.)

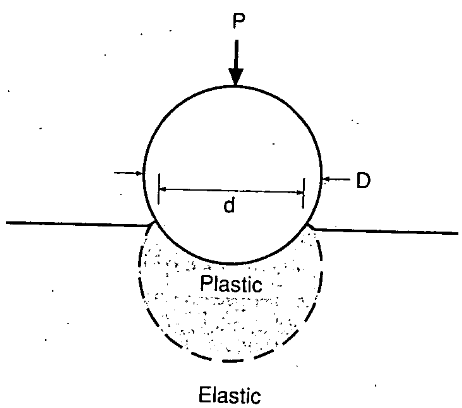

Figure 4.27 Plastic deformation under a Brinell hardness indenter.

.7 HARDNESS TESTS

In engineering, hardness is most commonly defined as the resistance of a material to *indentation*. Indentation is the pressing of a hard round ball or point against the material sample with a known force, so that a depression is made. The depression, or indentation, results from plastic deformation beneath the indenter as shown in Fig. 4.27. Some specific characteristic of the indentation, such as its size or depth, is then taken as a measure of hardness.

Other principles are also used to measure hardness. For example, the *Scleroscope hardness test* is a rebound test that employs a hammer with a rounded diamond tip. This